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# HOLOGRAPHIC OPTICAL HEAD

Holometrix, Inc.

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An experimental optical head using (HOEs) has been set up in our laboratory. The observed reconstructed spot size is less than 2 µm in diameter. Wavelength tolerance is ± 5nm centered at 832 nm. A new design using two aspherical lenses and two HOEs would operate over ± 15 nm. The new design can be the basis of a practical, highly compact, and reliable optical head. Performance can be significantly enhanced by using an e-beam pattern generator to fabricate an intermediate CGH needed to process the working HOEs. This will simplify the fabrication procedure and greatly reduce fabrication errors. Significant progress has also been made in developing a technique to make high-efficiency volume IR holograms, whose diffraction efficiency may approach 100%. This technique is unique and has not been reported in the literature by other researchers. Continuing effort is recommended to use an e-beam pattern generator to fabricate the intermediate HOEs, to design and fabricate high efficiency volume HOEs, to build an advanced engineering model HOH based on the aspheric design.

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and to investigate the potential for dramatically improved performance inherent in the knowledge base developed under this program.

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## GLOSSARY

**Binary hologram:** A hologram in which the fringes are of uniform optical density, in transmission holograms typically high density black lines.

**Bragg hologram:** A volume hologram formed in thick photopolymer for which the Bragg condition is satisfied.

**CGH:** Computer Generated Hologram; always computer designed, sometimes fabricated by direct photoreduction of computer output plots, sometimes fabricated by e-beam exposure of photoresist covered glass.

**COE:** Conventional Optical Element.

**Color Correction:** Balancing of HOE dispersion and COE chromatic aberrations so that the HOH performance is independent of source wavelength over some range of wavelengths.

**Diffraction efficiency:** The ratio of the power in the first order diffracted beam to the power in the incident beam. Typical diffraction efficiencies: binary transmission HOE, less than 10%; sinusoidal absorption HOE, less than 6%; phase HOE, 40%; Bragg HOE, approaching 100%.

**Dispersion Compensation:** (1) A technique which permits the balancing of the wavelength sensitivity of individual HOEs between members of a HOE-pair; (2) combining the mutual compensation of a HOE-pair with correction for chromatic aberration of COEs present in the HOH. Each HOE corrects for the residual aberration of its closest neighboring COE.

**HOE:** Holographic Optical Element.

**HOE-pair:** Holographic optical element consisting of a matched pair of HOEs designed to work in tandem for dispersion compensation and beam shaping.

**HOH:** Holographic Optical Head. An optical head containing HOEs.

**Hybrid head:** HOH containing both HOEs and COEs.

**Intermediate HOE:** HOE used to make a working HOE. An intermediate HOE is usually computer designed.

**IR hologram:** Infrared hologram, used in the infrared. Present technology does not permit direct exposure of IR holograms at their working wave length because IR-sensitive photoresist is not available.

**Sinusoidal hologram:** A hologram in which the fringes vary approximately sinusoidally in optical density, typical of a hologram generated directly by interference of two beams.

**Spot size:** The diameter at which the power density of a focussed beam falls to one-half its maximum value (FWHM).

**Working HOE:** Hologram used in an optical head.

# 1.0 INTRODUCTION

## 1.1 Program Goals, Scope, and Achievements

The objective of this program was to show the feasibility and advantages of holographic optical elements (HOEs) for use in optical disk read/write heads. Specifically, the feasibility of using HOEs in an optical head that (1) operates at laser diode wavelengths (780 or 830 nanometers) and (2) can achieve a one-micron diffraction-limited spot was to be demonstrated by design and verifying measurements.

These goals have largely been achieved, despite severe difficulties in the confirmatory measurement process. Furthermore, the utility and practicality of this approach has been greatly enhanced by the recent successful introduction of the single element aspheric objective lens in read/write optical head design. Aspheric objectives currently are the closest approximation to the ideal read/write lens: they are rugged, lighter than multi-element objectives and appear capable of smaller spot sizes. However, their performance is limited by chromatic aberrations. Other aberrations are, at least in principal, controllable, but any optical head objective using only single element glass optics, even aspheres, can not avoid chromatic degradation. Considering that the spectral bandwidth of diode laser sources is only a few nanometers[1], it is a remarkable testimony to the optical quality of these lenses that they are color limited. It also implies that no conventional lens is likely to afford further major improvements in spot size. It is precisely for correction of small residual aberrations, especially wavelength dependent ones, that holographic optical elements are most suited.

Specific achievements of the program are as follows:

1. Near diffraction-limited performance has been demonstrated: spot size of less than 2 microns full width with clear diffraction rings.

2. Color correction over a range greater than ± 5 nanometers has been demonstrated.

3. Calculational techniques have been significantly improved. Design characteristics can be determined and performance predictions can now be accomplished using the standard optical design program Super Oslo[2] in conjunction with special routines written in FORTRAN.

4. A new optical head has been designed using two aspheric lenses (to date, we have used two plano-convex lenses) which we calculate to produce diffraction-limited spots over a spectral range of +/- 15 nanometers. If achieved in practice, this degree of dispersion compensation will permit diffraction-limited operation over a temperature range of +/- 40 °C. Furthermore, this performance is achieved without need to refocus the system as laser wavelength changes.

5. The jigs and fixtures needed for fabrication of HOE-pairs have been reworked and improved, making it possible to produce HOE-pairs with better performance than already observed.

6. Extensive tests have been run on a commercial apparatus (the SpotScan[3] 0390) which, we believe is the optimum instrument available for verifying sub-micron spot sizes in a workable configuration.

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[1] Typical spectral bandwidths of laser diodes used in read/write applications are 3 - 5 nanometers, with temperature drift of approximately - 0.3 nanometers per °C.

[2] Super Oslo is a registered trademark of Sinclair Optics, Inc.

[3] SpotScan is a registered trademark of Photon, Inc.

7. Intensive efforts to interface our Computer Generated Hologram (CGH) designs to electron-beam (e-beam) machine input requirements have had positive results. Two e-beam facilities have been identified which can generate and are willing to attempt e-beam holograms for us. Although details still need to be worked out, it appears that this technology will be available to simplify the fabrication procedure and reduce fabrication errors.

8. Significant progress has also been made in developing a technique to make volume infra-red (IR) holograms, which are known to have diffraction efficiency approaching 100%. This technique is unique and has not been reported in the literature by other researchers.

## 1.2 Background Information

### 1.2.1 The Need

The rapid development of modern micro-computers has created a requirement for low cost mass data storage, especially in the military environment. Optical disk technology is now maturing and is ideally suited for this application. A key component of an optical disk system is the optical head. However, optical heads made with conventional optical elements (COEs) severely limit read/write system performance because they are complex, relatively heavy and large. They are also a significant cost element. (These conditions do not apply to the commercial audio compact disk where laser power for writing is not an issue and where read errors are usually not observable by the human ear.) Conventional optical elements are used in the optical heads for a group of related optical storage systems like CD-ROM (Compact Disk-Read Only Memory), WORM (Write-Once-Read-Many) drives, and erasable optical disks.

If we can improve the performance and reliability of the optical head and reduce its size, mass and cost, optical disk systems, particularly the erasable disk system, could become better adapted for military computer systems. More particularly, an increase in storage capacity by 100 times is likely to be possible with smaller spot sizes.

There are many commercial optical heads on the market. However, these optical heads are composed of bulky lenses, prisms, beamsplitters, etc. With conventional elements, it is difficult to reduce the size and weight of the optical head. The recent introduction of aspheric lenses has reduced the complexity of one component of the conventional head, but beam shaping prisms (to render the elliptical laser beam into a circular cross section) are still required.

In the read/write optical head, wavelength compensation becomes a very important because compensating for chromatic aberrations requires multi-element lenses to maintain a small focal spot. Uncompensated aberrations reduce depth of focus because of the resulting large focal spot size. Shallow depth of focus, in turn, increases the demands put on the optical head servos and today limits performance for read/write operation (or even for reading high density pre-written data). Faster servos are larger and more massive.

Thus, conventional technology is about at its limit. Smaller spots, which permit greater data density and higher data rates, now seem to require larger and heavier heads which limit servo response time and also the number of heads possible per disk. This severely limits access time and has a small negative effect on data rate once the data has been accessed.

Also it may be possible to equip an optical disk with several small holographic optical heads which would reduce access time in proportion to the number of heads.

High density optical disk are commercially available: small disks up to 300 Megabytes capacity, and large disk up to 10 Gigabytes. This capacity is needed for tactical military data storage. Thus, developing optical heads with high response speed becomes urgent.

### 1.2.2 Technical Background

Practical optical disk storage systems all use semiconductor diode laser sources because they are small, rugged, reliable, and energy efficient. Unfortunately their output has several undesirable characteristics: (1) The beam divergence is large and different in the planes parallel and perpendicular to the laser stripe. This leads to elliptical beam cross sections. For consumer products (audio compact disks), the beam is clipped to a circular cross section, which is very wasteful of energy; (2) The relatively low power output of a semiconductor diode puts a premium on using all its output for writing data to optical disks. Writing uses much more energy than reading, and wasting any laser energy reduces writing speed. Also spot shape is elliptical unless the beam is circularized properly, which clipping does not really accomplish. Therefore, prism pairs are universally used to circularize the beam; (3) the output is several nanometers wide and drifts with temperature. Conventional heads rely on the use of multiple elements to achieve good image quality and spectral tolerance. A single aspheric element can produce an excellent image but can not control chromatic aberrations at the same time.

In principle, holographic elements, used in the pair arrangement developed at the University of Delaware, can simultaneously correct for the astigmatism of the laser source, for the spectral dispersion of the individual holograms and chromatic aberrations of the focussing elements, replace the complex beam shaping elements, and also correct for other residual aberrations. If successful, such a hybrid head could be smaller, less massive, less expensive, and more reliable than its conventional counterpart. Before embarking on an ambitious program to produce a working optical head, questions concerning spot size, dispersion compensation, and efficiency all needed to be answered in a laboratory model small enough to ensure packaging of an advanced model.

It was to address these questions that the present demonstration program was initiated. A pair of holograms were to be used in conjunction with a pair of simple plano-convex lenses to demonstrate near diffraction-limited operation (one micron goal), small package size, dispersion compensation at least in the laboratory environment, and scalability to a working optical head. Ancillary questions of fabricability were also to be addressed.

## 1.3 Results and Recommendations

An experimental optical head using HOEs has been set up in our laboratory. The observed reconstructed spot size is less than 2 $\mu$m in diameter. Wavelength tolerance is $\pm$ 5 nm centered at 832 nm. A new design using two aspherical lenses and two HOEs would operate over $\pm$ 15 nm. The new design can be the basis of a practical, highly compact, and reliable optical head. Performance can be significantly enhanced by using an e-beam pattern generator to fabricate an intermediate CGH needed to process the working HOEs. This will simplify the fabrication procedure and greatly reduce fabrication errors.

Significant progress has also been made in developing a technique to make high-efficiency volume IR holograms, whose diffraction efficiency may approach 100%. This technique is unique and has not been reported in the literature by other researchers.

Continuing effort is recommended to use an e-beam pattern generator to fabricate the intermediate HOEs, to design and fabricate high efficiency volume HOEs, to build an advanced engineering model HOH based on the aspheric design, and to investigate the potential for dramatically improved performance inherent in the knowledge base developed under this program.

# 2.0 TECHNICAL DISCUSSION

## 2.1 Technical Approach

### 2.1.1 The Optical Layout and Its Rationale

The experimental system involves two single-element plano-convex lenses and two holograms. This configuration can correct the ellipticity of the laser beam and provide diffraction-limited performance. As shown in Fig. 1, the optical configuration consists of a laser diode, S, a collimating lens, *L1*, a compensation hologram, *H1*, a main hologram, *H2*, and an objective lens, L2. The output of the laser is roughly collimated by the collimating lens. The simple collimating lens is inherently highly aberrated and is working at a high numerical aperture (approximately $f^{\#}1$), so that perfect collimation would not be possible in any event. Additionally, optimization of system performance over a band of wavelengths is achieved with a slightly uncollimated wave front impinging on the compensation hologram. The compensation hologram performs two functions: (1) it corrects the incident wave front for the aberrations induced by the collimating lens, and (2) it diffracts the incident rays through a large angle which changes the beam cross section. As will be shown, the wave front emerging from the compensation hologram would ideally be perfectly collimated and normal to the hologram plane.

Because the optical axes of the incident and exiting beams are not parallel, these beams have different diameters. Thus, the beam shape factor (ellipticity) is changed by *H1* from 2.69 to 1.39. *H2* reduces the ellipticity factor to unity.

The main hologram, *H2*, also deliberately aberrates the transiting wave front to pre-compensate the aberrations induced by the objective lens. (The wave front exiting from *H2* is designed to be identical to the wave front which would be propagated by *L2* from a point source in the desired focal plane, except that the propagation direction is reversed.) That is, the beam propagated from *H2* exactly compensates for the aberrations of the objective. Thus a diffraction-limited spot can be formed by the objective, at least at the design wavelength.

The HOE-pair, acting together compensate for the wavelength drift of the laser source and for the inherent wavelength sensitivity (chromatism) of the system components.

Either the angle of incidence on the compensation hologram or the angle between the compensation and main holograms is a free parameter. (Together they must provide beam circularization.) They can be chosen to maximize the wavelength range over which the HOE-pair can produce a diffraction-limited spot. Without aberrated lenses, this angle can be specified analytically; in practice, iterated calculations are needed to optimize performance.

Holograms are diffraction gratings on which the grating parameters can be locally controlled. They are formed by interfering "reference" and "object" beams on a photo-sensitive substrate so that the interference pattern maxima expose the substrate in the desired grating pattern. Being diffraction gratings, they disperse incident radiation through wide angles, depending on wavelength. By operating a pair of identical parallel diffraction gratings or HOEs (Sincerbox, in References) in equal but opposite orders (+1 and -1), the net angular dispersion can be made to vanish for an incident beam. In our case, the HOE-pair members can not be identical because it is made inherently asymmetric to correct beam ellipticity. Nonetheless, dispersion can be minimized at a single design wavelength. The design question then becomes trading off dispersion compensation for aberration correction of the lenses. That this can be done successfully is demonstrated by the results of this program.

Plano-convex lenses are the simplest possible lens and have very large aberrations. Their choice was intended to demonstrate the power of our technique. Within our ability to measure the results, this aspect of the design appears to be successful.

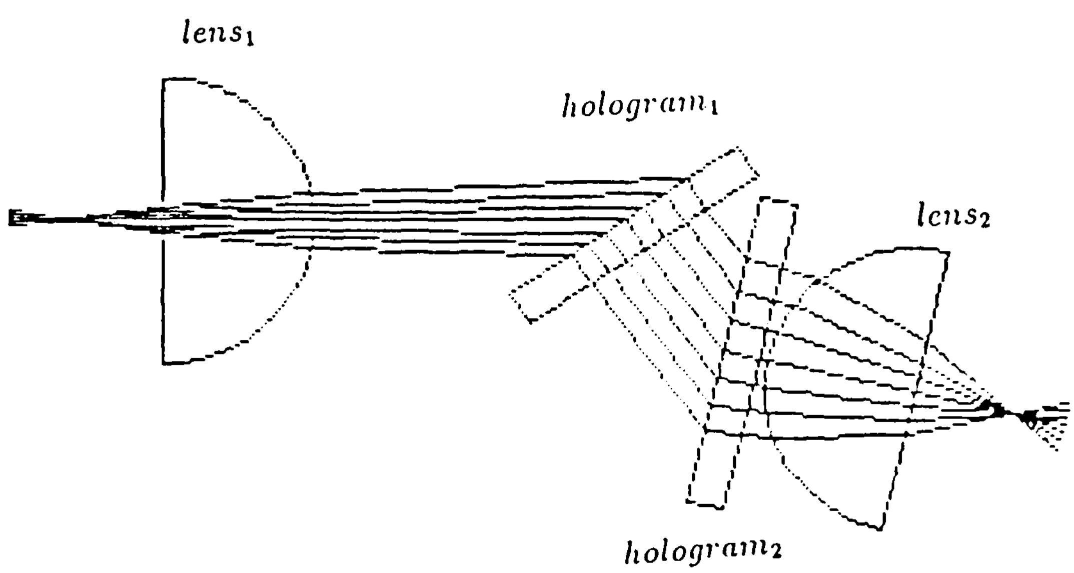


Fig. 1 Configuration of the Baseline Optical Head.

However, well corrected single-element aspheres are a better candidate for a future system. Because they are single elements, molded aspheres can not compensate for chromatic aberration. Multiple element systems can, but they suffer from other residual aberrations and fabrication problems. The combination of a wavelength compensating dual-HOE and a pair of molded single element aspheres is likely to yield sub-micron spots with wide temperature (read dispersion) compensation.

### 2.1.2 Design of the HOE-pair

Design of the HOE-pair has been reduced to calculation of the parameters necessary to compensate for laser wavelength drift and lens aberrations. For reasons to be explicated below, it is necessary to fabricate the HOE-pair through the use of an intermediate hologram.

Note that we determined what the second HOE should do to the wave front incident upon it by specifying the desired output (a diffraction-limited point in the focal plane). That output from the physical hologram is called the "reconstructed" beam because it reconstructs the output of the desired ideal optical system. Similarly, the beam which is used to illuminate the physical hologram is called the "construction" beam.

As mentioned above, the object and reference beams are used to fabricate the hologram. If space permitted and if IR sensitive photoresist were available, the object beam could be generated by passing laser radiation through the actual optical subsystem whose aberrations we want to correct. The reference beam is frequently a physical beam identical to the desired construction beam except in orientation. (It is the conjugate of the construction beam.) The reference beam is directed at the photosensitive surface so that the interference pattern resulting from its interaction with the object beam would make a hologram that properly redirects the reconstruction beam. Because the wave front between the holograms is collimated to first order, the reference beam used in making either hologram is also nearly collimated, a condition important to making high quality holograms at one wavelength for use at another. Either the reference beam or, more frequently, the object beam can itself be deliberately distorted, for example in our case, to compensate for the fact that the object and construction beams must be of different wavelength.

In our case, where it is not feasible to use a real optical system to generate the master reference wave front, a "synthetic" Computer Generated Hologram (CGH) can be used to generate the working HOE. [Ih, et al (1986a, 1986b)], [Wyant (1978)]

After computing the design of the optical system and analyzing its performance, fabricating the HOE-pair becomes the key factor in realizing the design.

Because the wavelength of laser diodes are in the near IR region, direct recording of these holograms is not feasible. First, recording photoresists sensitive to the laser wavelength are not commercially available. In fact, none of the vendors we have approached will admit to having such photoresists in development, although there persist unconfirmed reports that at least one manufacturer has developed the requisite technology. However, even if IR-sensitive photoresist were available, they would not be useful in fabricating HOEs for a practical optical head: the hybrid head optical layout is too compact to allow introducing a collimated reference beam to interfere with an object beam passed through a collimating lens. Therefore, direct in-place generation of the HOE-pair by interfering beams is out of the question, and the alternative CGH route was taken.

There are two possible approaches to HOE construction without interfering physical beams. The first, discussed above briefly, involves computer generating an intermediate HOE which can then be used to distort the object beam to make the working HOE. The intermediate HOEs can be generated optically or by using an e-beam pattern generator designed for manufacturing reticles (masks) for semiconductor integrated circuit fabrication. The second approach involves attempting to use an e-beam apparatus to generate the working HOEs directly. Each approach has its own peculiarities which we have not fully resolved.

E-beam generation of the final HOEs requires using an e-beam pattern generator at the limits of its capability. Because these machines are designed to generate reticles for integrated circuit production, they are not ideally suited for generating our final HOEs. Our working HOEs are approximately 3 mm in diameter with up to 1,000 steeply curved contour lines per millimeter. Typical reticle patterns are smaller, much less dense and rectilinear. As a result, the data needed to drive a typical e-beam apparatus can overwhelm many of the standard input schemes. Also, most mask makers do not have the appropriate experience for our needs. The joint problem of input and experience has been addressed, and direct generation of masters from which the final HOEs can be contact printed appears worth further pursuit. See Section 2.2.2.

Because of the large size of our HOEs, e-beam generation of oversize reticles followed by conventional photo-lithographic reduction is also impractical. Generation of intermediate HOEs by e-beam apparatus does appear to be practical. To date, however, we have employed optical techniques to fabricate intermediate HOEs.

2.1.3 Theory

Introduction. The concept entailed in the use of an intermediate computer-generated HOE to fabricate a working HOE is simple. For example, the desired output wave front from the first working hologram, the compensation hologram, is known. It is simply the perfectly collimated beam from an ideal collimating lens with a point source at its focal point. Because the parameters of the real source and collimating lens are known, it is possible to calculate the actual wave front impinging on the hologram plane, and thus to compute and produce the intermediate HOE.

Because this object-beam-distorting-hologram can be made independently of the working system, there is great freedom in designing it. In fact, the angle between the reference and object beams can be made very small, which results in consecutive interference maxima being far apart. This means that the distortion hologram may have only a few hundred contours rather than several thousand.

Also, because interference effects scale directly with wavelength, it is possible to design the compensation hologram to be manufactured using light at one wavelength but used at another wavelength. This technique is called two-wavelength operation. In our case, the distortion HOE can be calculated to expose the plate carrying the photoresist for the working HOE with an argon ion or helium-cadmium laser. The distortion HOE simply compensates for the fact that the working HOE will operate in the near IR. The specialized computer programs developed to design the working HOEs and the computer generated precursor distortion HOE have been greatly improved during the course of this program.

In practice a distortion CGH is pen-plotted many times oversize and photoreduced to the correct size to generate its associated working HOE. As may be expected, this is a difficult and delicate operation, made possible only by the relative coarseness of the distortion HOE. Even so, the process is prone to errors, which provided the motivation for our intensive investigation of using an e-beam apparatus for generating the intermediate HOE; see Section 2.2.2. For a discussion of the accuracy requirements for two-wavelength operation, see Wyant (1978).

Here we outline the procedure for making a working HOE using an intermediate CGH; detailed descriptions are given in Ih, et all (1988 and 1989a).

First, the desired wave fronts of the object and reference beams of the working HOE at its working wavelength are defined mathematically. We then determine the size, spatial frequency and resolution of an intermediate CGH which is consistent with the available equipment. The CGH is then computer calculated by reconstructing the working hologram at the chosen recording wavelength. Accurate tracing of rays through the system described below enables the computer automatically to include aberrations introduced by lenses in the beam paths.

After the intermediate HOE is designed and built, it is used to (re)create a distorted objective beam. This distorted beam and an appropriate reference beam are superposed upon a photosensitive substrate to make the working HOE. Fig. 2 illustrates the process.

In summary, the beam distorting intermediate CGH is designed to compensate for the fact that the working HOE is fabricated at a wavelength different from its working wavelength. The parameters of the intermediate CGH are calculated by determining what the working HOE should be, then calculating what the working HOE output (reconstructed) beam would be if the input to it were at the fabrication wavelength. The calculation continues by propagating this output to some convenient location and superposing it there with a new reference beam at the fabrication wavelength. The interference pattern at this convenient location defines the beam distorting CGH. When properly conjugated (object and reference) beams at the fabrication wavelength are directed at a photosensitive surface with a physical realization of the intermediate CGH in one beam (usually the object beam), the desired working HOE is produced.

This technique has several other desirable features. Large HOEs with high spatial frequency can be made easily, even on curved surfaces, and, because the working HOE is made optically, we have a wide choice of recording materials. This method can also be extended to use visible light to make high efficiency Bragg (volume) IR HOEs; see Section 2.2.4. Thus, the CGH provides a powerful technique to solve the difficulties mentioned above.

There are many ways available to fabricate the intermediate HOE. ˉ our HOH application, an interferogram type CGH is preferred because of its diffraction limit performance and low noise reconstruction. Therefore, we evaluate the interference pattern to calculate the location on the CGH of the interference fringes one by one. Because the curvature of the fringes is quite small, it is sufficient to calculate the location of only a small number of points on each fringe. A simple computer algorithm, normally a spline fit, is used to connect these points to form a smooth curve. Then, when the reconstructed beam is traced through the hologram, the parameters of the diffracted ray can be calculated.

Calculation of a CGH is tedious but straightforward for systems involving only conventional optics and interfering beams. However, as explained above, design of the intermediate CGH requires calculating the propagation of beams through the conventional optics, which shape the object beam, and through the desired working HOE. The introduction of the desired HOE into the optical path calculations is complicated by the fact that the rays from successive fringes on the working HOE introduce additional phase changes. (This phenomenon is related to the introduction of secondary structure in the output of an ordinary diffraction grating.) The additional phase change must be treated correctly; we have developed two methods which do so and use both of them in each calculation as a check on accuracy and convergence.

Calculation of CGH Parameters. A brief description of the theory of the holographic optical head follows. For a more exhaustive treatment, see References.

The CGH we made is an off-axis reference beam hologram. The amplitude transmittance of a hologram is given by

$$t(x,y) = 0.5\{1+\cos[\Phi_r(x,y)-\Phi_o(x,y)]\},$$

where $\Phi_r(x,y)$ and $\Phi_o(x,y)$ are the phases of the reference and object beams used to record the hologram.

The maxima fall at

$$\Phi_r(x,y) - \Phi_o(x,y) = 2n\pi.$$

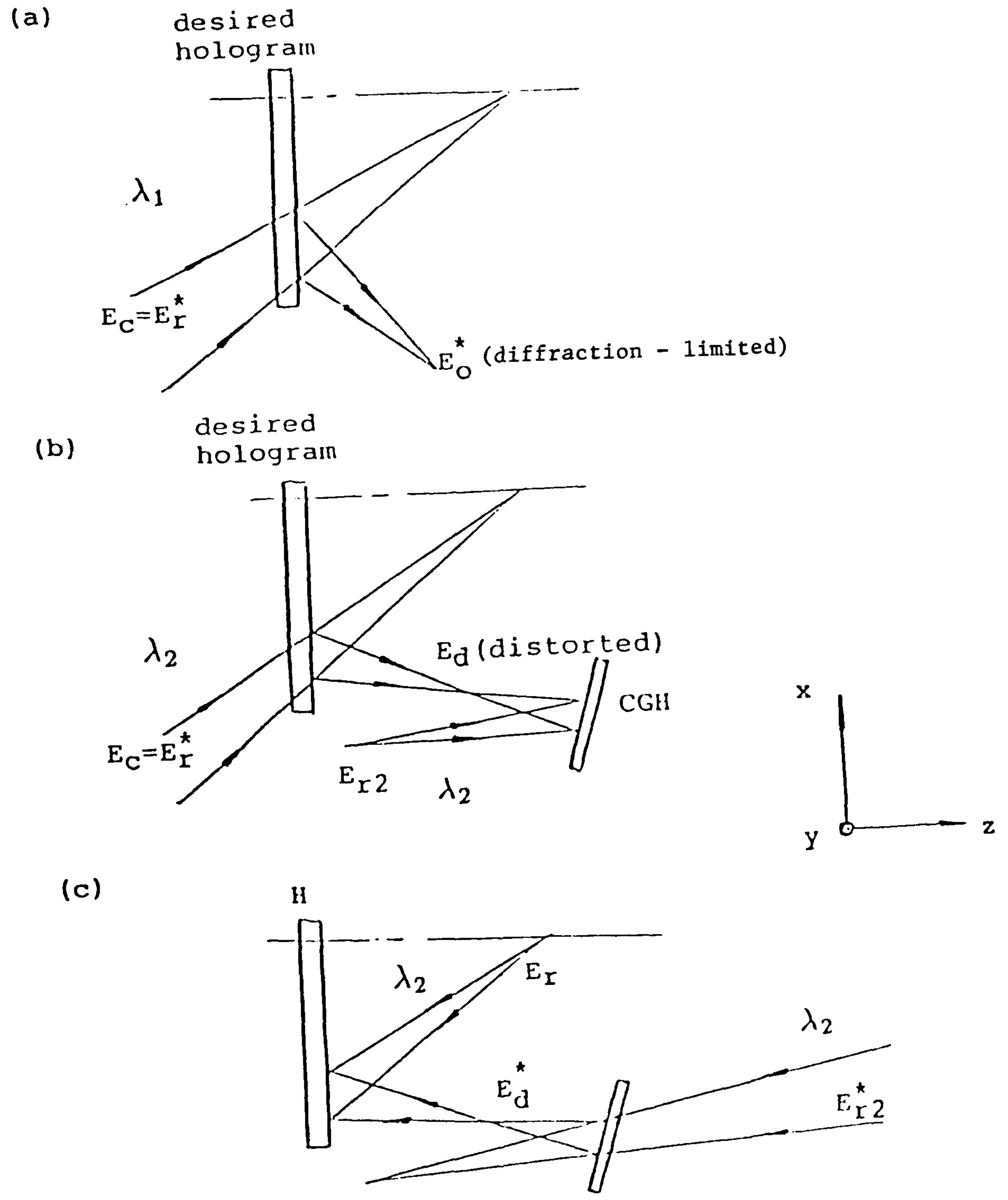


Fig. 2 Use of Intermediate Computer Generated Holograms to Produce a Working HOE.

Analytic conditions on the chief ray can be determined in the absence of aberrations, which provides a crude estimate for starting the calculation. To design the CGH, the computer program performs light ray tracing (because light rays are normals to the wave front) and then finds the phase of the deformed wave by calculating the optical path length. Unfortunately, the individual hologram grating constants are known only on the calculational grid attached to that hologram. Therefore, it is not possible simply to trace a fan of rays through the system starting either at the laser, or at the focal point. To a first approximation, the compensation and main holograms can be calculated independently, but the piercing points of arbitrary rays traced forward from the calculational grid of the compensation HOE to the main HOE do not coincide with known points on the calculational grid of the main HOE, and *vice versa*. Therefore, we solve the ray trace iteratively, first defining the HOEs separately, then tracing rays through them, then interpolating in a coordinate system attached to each surface, then retracing. This process is repeated until an equitably distributed fan of rays is traced to a converged solution.

Here the vector form of geometric optics is preferred for the ray trace. First, for each ray traced, the coordinate points are determined on each surface intersected. Then its direction cosine is calculated.

For a refracting surface, the governing equation is Snell's law, given here in vector form.

$$n_f \hat{r}_{in} \times \hat{n} = n'_f \hat{r}_{ex} \times \hat{n}$$

where $n_f$ and $n'_f$ are the refractive indices of the media before and after the surface, $\hat{r}_{in}$ and $\hat{r}_{ex}$ are unit normals along the incident and refracted rays, and $\hat{n}$ is a unit normal to the surface.

If the surface is a hologram, Welford's equation is used instead of Snell's Law.

$$\hat{n}_c \times (\hat{r}_d - \hat{r}_c) = m\,(\lambda_c/\lambda)\,[\hat{n}_r \times (\hat{r}_o - \hat{r}_r)]$$

where $\hat{r}_o$, $\hat{r}_r$, and $\hat{n}_r$ are, respectively, the unit vectors for the object beam, the reference beam, and the normal to the hologram surface in the recording process. Similarly, $\hat{r}_c$, $\hat{r}_d$, and $\hat{n}_c$ are the unit vectors of the reconstruction beam, the reconstructed beam, and the normal to the surface of the hologram in the reconstructing process; $\lambda$ and $\lambda_c$ are the wavelengths in the recording and reconstruction process respectively; and m is the diffraction order. In this way we can get the intersection points (x', y', z') and the direction cosine of the refracted ray, (l',m',n'). These data permit propagation of the ray to the next surface. There a new coordinate system is established, and the tracing continues as above, using either Snell's or Welford's formulation. Ray tracing is stopped when the ray reaches the image plane.

In order to find the phase of the deformed wave, $E_d$, we can use the grating equation

$$d(\sin\theta_i + \sin\theta_d) = m\lambda \qquad (m = 0, \pm 1, \pm 2, ...)$$

(and the fact that light rays are normals to the wave front) to determine optical path and, therefore, phase. Alternatively, we can use the eikonal equation to determine optical path.

$$\hat{s} = \mathrm{grad}\theta / |\mathrm{grad}\theta|$$

As discussed above, we use both techniques and compare them as a check on calculational accuracy.

<u>Two-wavelength Operation</u>. A hologram can easily be exposed at one discrete wavelength and used at another discrete wavelength, a process usually called two-wavelength operation. It is necessary only to ensure that, at all points,

$$[\sin\{\Theta_i(\lambda_1)\} + \sin\{\Theta_d(\lambda_1)\}]/\lambda_1 = [\sin\{\Theta_i(\lambda_2)\} + \sin\{\Theta_d(\lambda_2)\}]/\lambda_2.$$

This condition can be easily satisfied with holograms made with plane waves (simple gratings).. In general, wave front phase distortions (or compensations) must be introduced into either the object or reference beam, or both, during the recording process. If high resolution and diffraction limited performance are not required, approximate methods have been developed to achieve the required results. However, for the HOH application, *high resolution and diffraction limited performance* are required. We have developed a unique method to generate a CGH, outlined above and in detail in Ih, et al (1988 and 1989a), which introduces the exact phase compensation into the object beam.

As described above, achieving the two-wavelength condition requires the introduction of a wave front distorting CGH into the object beam used to make the working HOE. These distortions guarantee satisfaction of the two-wavelength condition when the distorted object beam is superposed with an appropriate reference beam to make the final working HOE; see Fig. 2.

Using this method, near diffraction limited performance has been demonstrated; a spot size less than 2 $\mu$m with clear diffraction rings. (We attribute not achieving the theoretical minimum spot to fabrication errors in making the CGH and misalignment of the fixturing used to generate the working HOE. See 2.1.5 for details of the fabrication procedure.)

<u>Dispersion Compensation</u>. Individual holograms are diffraction gratings and exquisitely sensitive to wavelength changes (highly dispersive); a single hologram can not be made even approximately dispersion free over a finite range of operating wavelengths. A HOE-pair is needed.

Also, because the asymmetric HOE-pair members are not simple gratings with the same unique spatial frequency, dispersion can not be completely compensated. However, dispersion can be made to vanish at a predetermined nominal operating wavelength, thus permitting satisfactory performance over a range of wavelengths centered on the perfectly compensated wavelength.

To achieve dispersion compensation between the members of the HOE-pair, it is necessary to determine conditions on the major free parameters of the optical layout which minimize dispersion. These parameters are the angle of incidence of the chief ray on the compensation HOE and on the angle between HOEs. (These two parameters are not independent; they are constrained by the requirement that the incident elliptical beam be circularized by the HOE-pair.) The range of dispersion compensation can then be determined numerically by investigating spot diagrams around the fully compensated wavelength. Fortunately, an analytic expression can be derived for an ideal unaberrated system in which the beam between the HOEs is strictly parallel. This provides the starting point for numerical calculations. Fig. 3 shows a convenient set of angular parameters, from which the angle between HOEs can be derived.

From the hologram equation, we have for the compensation and main holograms, *H1* and *H2*, respectively,

$$a(\sin\Theta_{o1} - \sin\Theta_{r1}) = \lambda$$

and

$$b(\sin\Theta_{o2} - \sin\Theta_{r2}) = \lambda$$

By manipulating the derivatives of these equations we find,

$$d\Theta_{o2}/d\lambda = -d\Theta_{r1}/d\lambda$$

From which we get

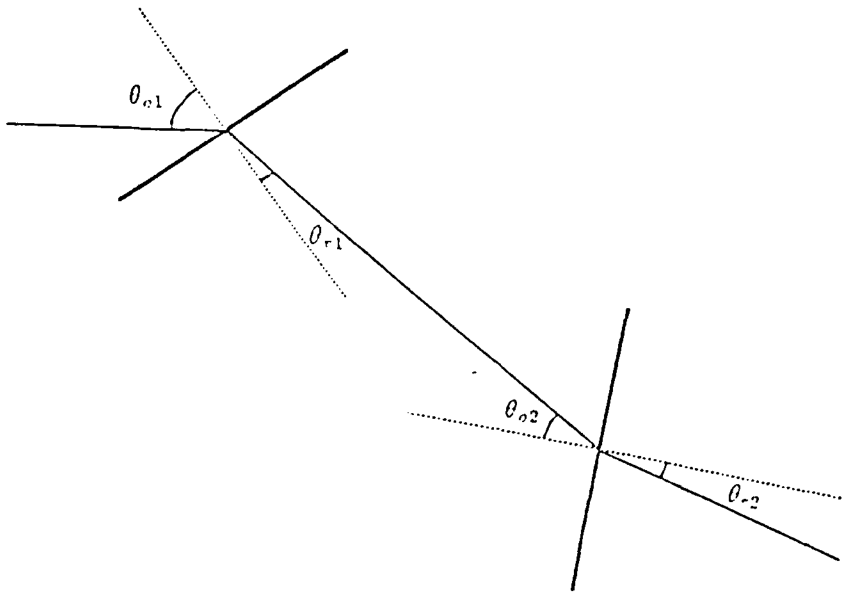


Fig. 3 Compensation Condition for a HOE-pair.

$$d\Theta_{r2}/d\lambda = (\sin\Theta_{r2} - \sin\Theta_{o2})/\lambda\cos\Theta_{r2} - \cos\Theta_{o2}(\sin\Theta_{r1} - \sin\Theta_{o1})/\lambda\cos\Theta_{r1}\cos\Theta_{r2} = 0,$$

and if

$$\Theta_{r1} = \Theta_{r2} = 0$$
$$\sin\Theta_{o1} = \tan\Theta_{o2},$$

then

$$d\Theta_{r2}/d\lambda = 0$$

which is the condition for perfect compensation.

Spot diagrams verifying system performance over a range of wavelengths about the nominal design wavelength are shown in Section 2.1.4. These ray traces automatically include lens aberrations and residual dispersion of the HOE-pair.

The criterion for acceptable performance is that the spot size must be less than one $\mu$m. The nominal design with which this program started is wavelength compensated over +/- 5 nanometers. The newer design using molded aspheric elements is compensated over +/- 15 nanometers.

Correction of Chromatic Aberration. In this subsection, we demonstrate the conditions for making a HOE correct the chromatic aberration of a lens. To correct the chromatic aberration of a lens used in an optical head, it is sufficient to hold the focal length constant over the desired wavelength range, because the lenses have minimal field. Therefore, we need only to determine the local grating spacing for a HOE coupled to a lens which holds the lens focal point constant over a range of a few

nanometers. To be concrete, consider the chief ray and any other arbitrary ray incident on the main HOE. It is sufficient to show that the optical path from HOE to focal point can be made the same for both rays. We do this for a thin lens; in reality, the condition is obtained by ray tracing.

From Fig. 1, it can be seen that the chief ray can be made to exit normal to the HOE by construction. Also, because the wave front between holograms is collimated, to first order all rays strike the main HOE at the same angle, $\beta$. See Fig. 4.

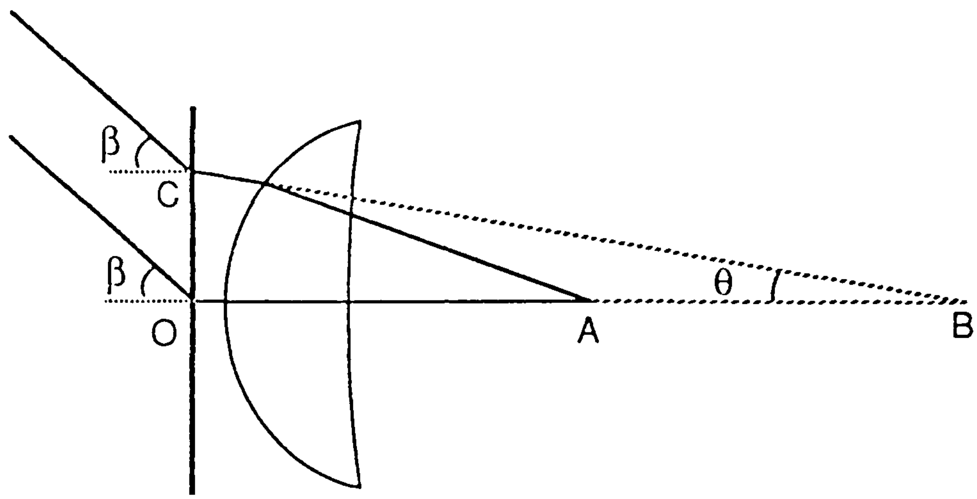


Fig. 4 Geometry of Chromatic Aberration correction.

The lens equation is

$$1/f(\lambda) = [n(\lambda) - 1]\ (1/r_1 - 1/r_2).$$

The grating equations for the arbitrary and chief rays are, respectively,

$$\sin\beta - \sin\Theta = \lambda/a$$

$$\sin\beta - \sin\Theta_1 = \lambda/a_1,$$

where a and $a_1$ are the fringe spacing on the HOE at *C* and *O*, respectively in Fig. 4, and $\Theta$ is the angle between the diffracted output ray and the normal to the HOE.

By definition, $\Theta_1 = 0$, so

$$\sin\Theta = \lambda/a_1 - \lambda/a.$$

From Fig. 4, we can obtain the relationship between the intercept height of the arbitrary ray, <OC>, and the focal length <OA>. This relationship can be found either by geometrical construction or by application of the optical invariant [Smith, page 42].

$$\langle OA\rangle = \langle OC\rangle[\langle OC\rangle[1/r_1 - 1/r_2][n(\lambda)-1] + \tan(\Theta)]^{-1}$$

If <OA> is nearly independent of wavelength, the system is chromatically corrected. Setting the derivative of <OA> with respect to wavelength equal to zero, and then making the obvious substitutions leads immediately to

$$d\langle OA\rangle/d\lambda = 0$$

when

$$\sin^2\Theta = 1 - [\langle OC\rangle(dn/d\lambda)[1/r_1 - 1/r_2)]^{-1}$$

This means that the lens can be chromatically corrected to first order by a properly designed HOE. With this as a starting point, a region in the neighborhood of the first order design can be explored to optimize a real system design.

### 2.1.4 Calculational Results

Design calculations were made for the baseline system which uses a pair of identical high index plano convex lenses. As a result of our improved calculational ability, we were also able to design a system using molded aspheric lenses with dramatically improved performance. Fig. 5 shows the layout of this configuration. This improved calculational ability also made the spot diagram calculations more accurate.

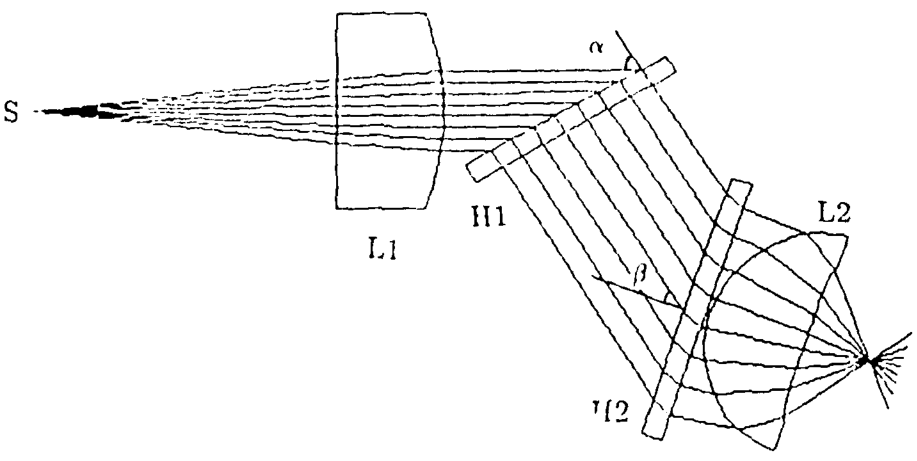


Fig. 5 Configuration of the Advanced Optical Head (Aspherical Optics)

Figs. 6, 7 and 8 are spot diagrams calculated for the baseline system. Fig. 6 was calculated for the nominal design operated at a wavelength of 837.0 nanometers, 5 nanometers more than the design wavelength of 832.0. A large majority of the rays fall well within a one micron spot, with four outliers slightly more than one micron apart. Fig. 7 shows that the design is tolerant of angular misalignment of the HOE-pair. Tilting the second HOE 0.5° out of alignment does not significantly increase spot size while operating at 837.0 nm. Fig. 8 shows the effects of incorporating a 4 micron axial displacement of the laser with the other misalignments; in this case, aberrations tend to cancei somewhat and the total spot lies within a one micron circle. In all three cases, the Reference Height (radial displacement of the nominal design chief ray) is negligible, less than $2.1 \times 10^{-15}$ mm. However, these spot diagrams are calculated at best focus; refocussing needed to optimize the focal position (given as FOCUS in the Figures) ranges from 7.9 to almost 8.7 microns. These tolerances are acceptable for tilt and axial displacement, which would either be build in as fabrication errors or, at worst, change slowly, perhaps with temperature, and would therefore be compensated by the optical head servo system. Wavelength change on the order of 5nm may not be so fast that the optical head servo would not follow the induced 8-9 $\mu$m focus shift, but this may be problematical in practice. Also, chromatic aberration of the lenses was not considered in these calculations. (Compensation for lens chromatic aberration has been shown to be feasible in Section 2.1.3).

Using our new computational capability, we calculated spot diagrams for a HOH using monolithic (singlet) molded aspherical lenses. Because their spherical aberration is much smaller than that of the baseline plano-convex lenses, we were able to design a 2 to 1 reducing system; the focal length of the collimating lens is twice that of the objective. Really significant improvement was found. This design can be recommended for a real system.

Figs. 9, 10, and 11 are spot diagrams for the aspheric design. They are similar to Figs. 5, 6, and 7, except that the operating wavelength has been shifted 15 nm from nominal. For the nominal system, and for the angularly misaligned system, the total spot size is well under 1/2 micron in diameter; with axial displacement of the laser, the spot is significantly smaller than one $\mu$m. <u>Most significantly, there is no need to refocus.</u>

With a +/- 15 nanometer wavelength range, this head would perform satisfactorily over a total range of about 80° C.

### 2.1.5 Fabrication of the HOE-pair

In addition to the iterative calculation which leads to an optimized design, numerous calculations near the nominal were made to determine tolerances for assembly, manufacture and for the working environment.

After calculation by the computer program, the CGH is plotted by a large pen plotter (Watanabe MP1000 or Tektronix 4663S). This calculation can now be performed on an AT class PC under DOS as well as on a Unix based VAX system.

The pen plotted CGH is then photoreduced, and the reduced plate mounted on a precision micrometer-controlled carrier and introduced into the object beam path. Meticulous adjustment is required. Finally, a blue laser beam at 441.6 nm is used to record the working HOE for use at 832.0 nm. The several steps required to produce a working HOE are shown in Fig. 2.

The output spot with plano convex lenses was measured in several ways. Although it was impractical to determine the Strehl ratio, the spot size is clearly less than 2 microns, a close approach to the diffraction limit for this system. The spot size for a diffraction-limited beam is $\alpha\lambda F^{\#}$. For an ideal point source, $\alpha = 2.44$ when the spot diameter is measured between the first zeros of the Airy pattern. For a $TEM_{00}$ Gaussian laser source $\alpha = 1.57$, where the spot is measured to the 1/e amplitude

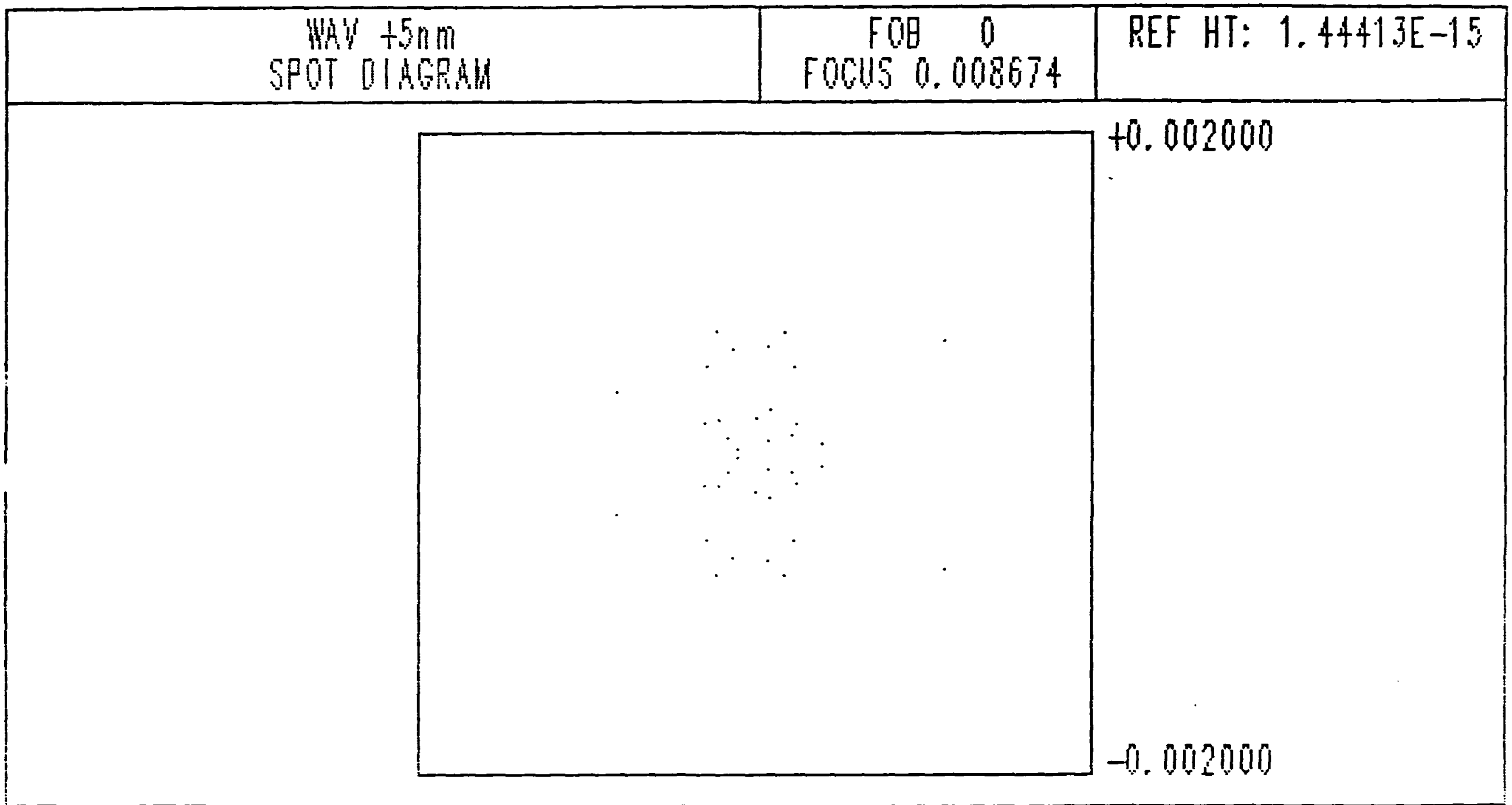


Fig. 6 Spot Diagram: Baseline Design with 5 Nanometers Wavelength Shift.

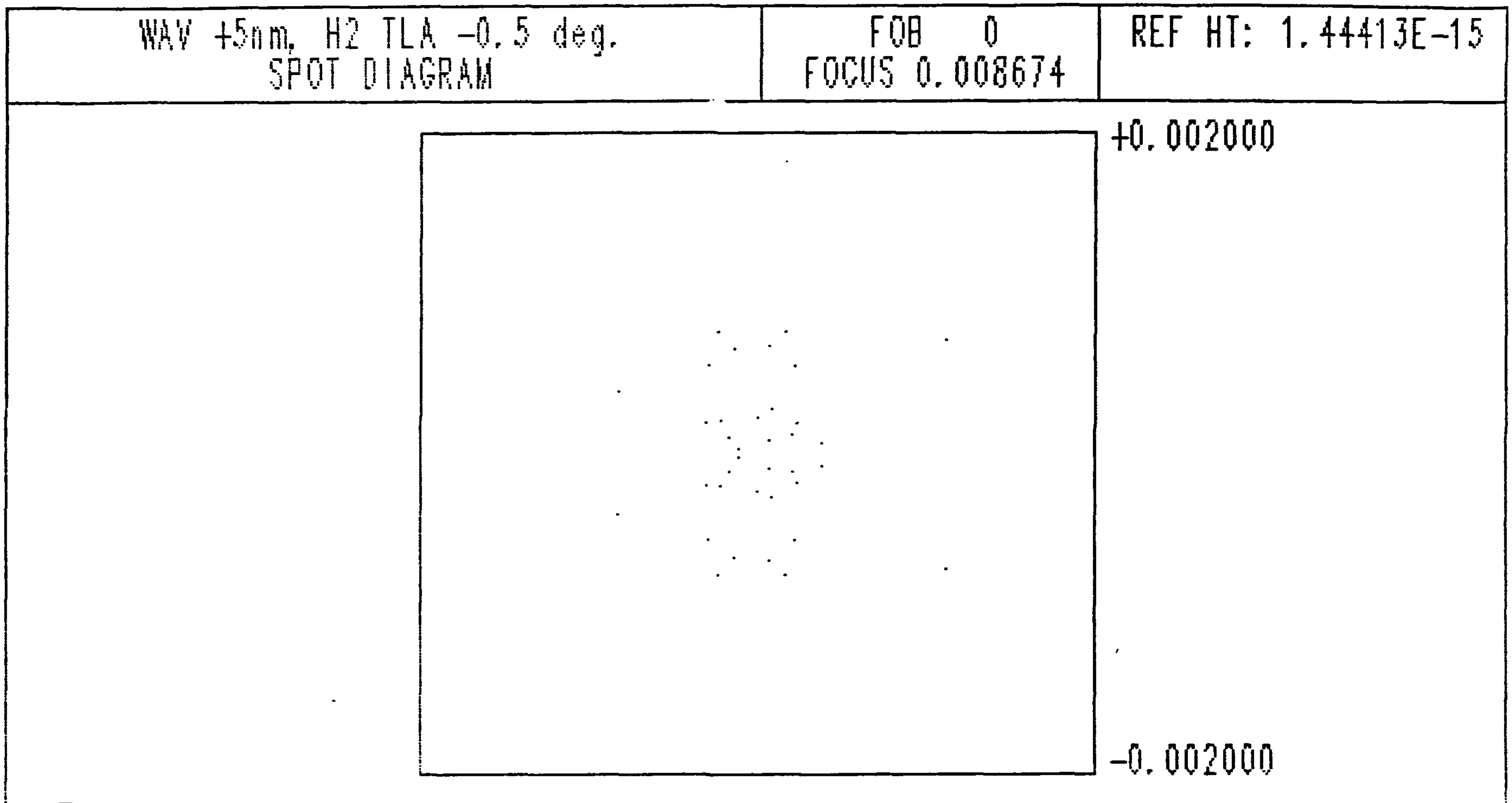


Fig. 7 Spot Diagram: Baseline Design with 5 Nanometers Wavelength Shift and 0.5° HOE-pair Misalignment.

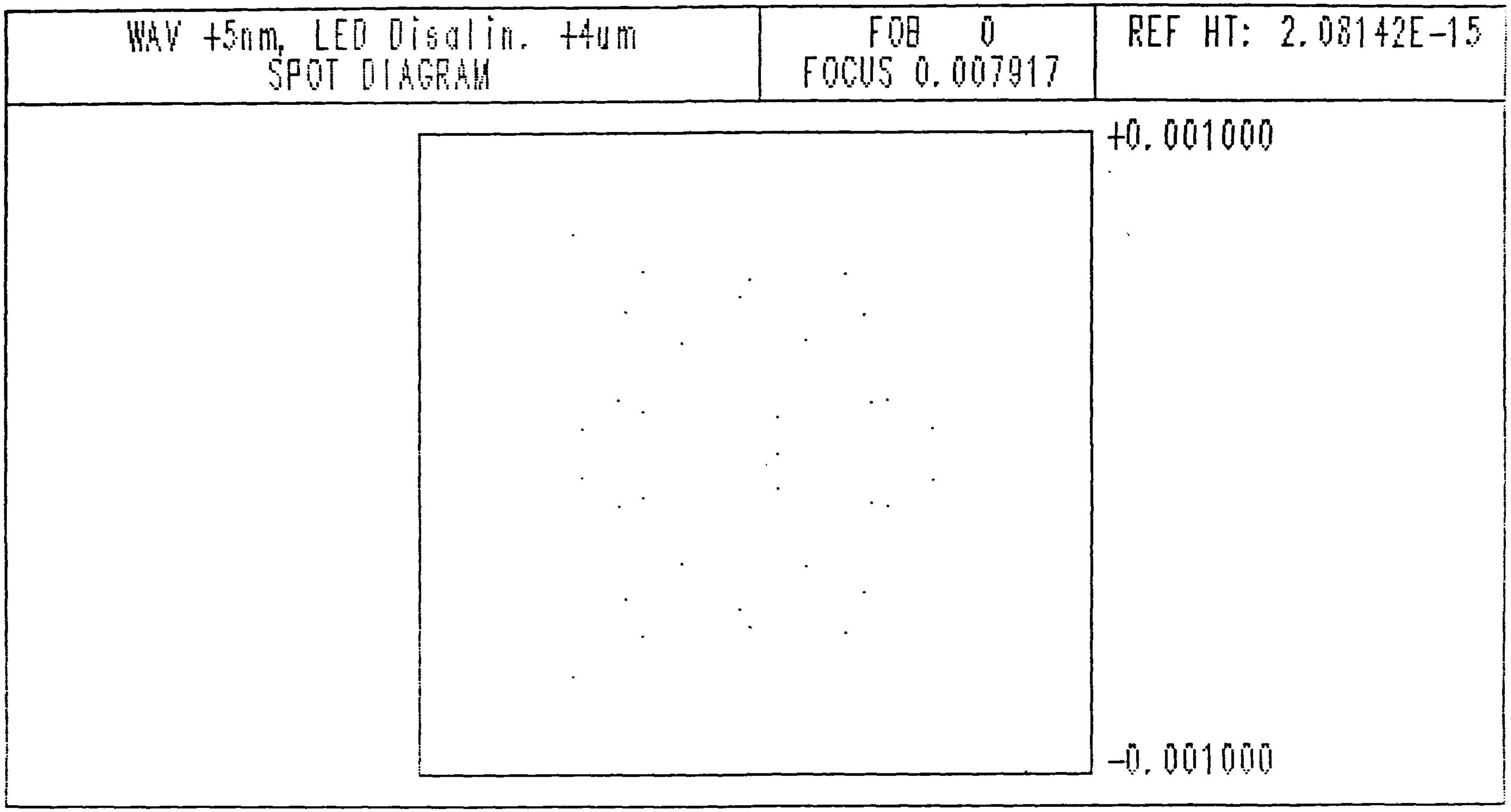


Fig. 8 Spot Diagram: Baseline Design with 5 Nanometers Wavelength Shift, 0.5° HOE-pair Misalignment, and 4 Micron Laser Axial Misalignment.

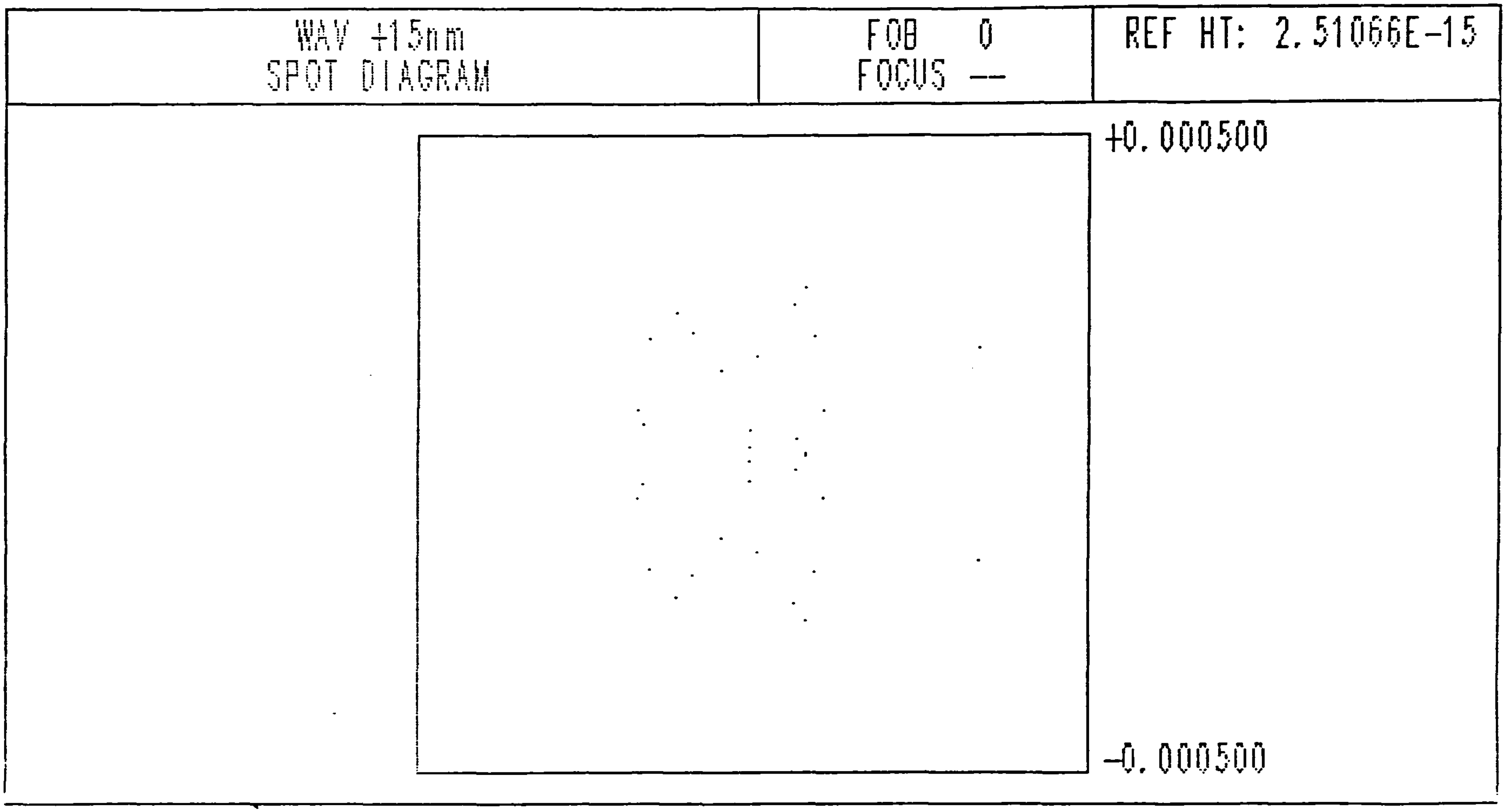


Fig. 9 Spot Diagram: Aspheric Design with 15 Nanometers Wavelength Shift.

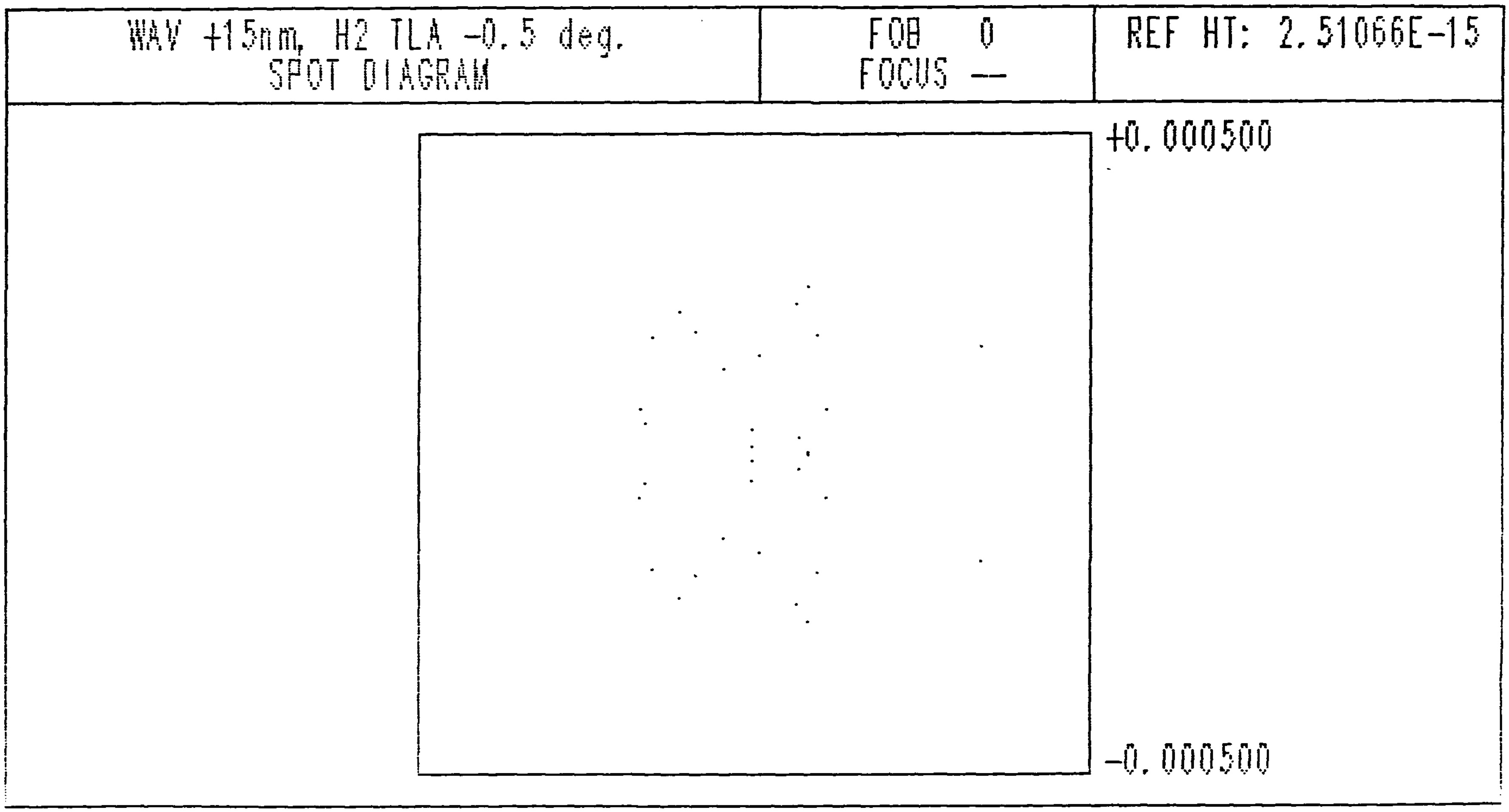


Fig. 10 Spot Diagram: Aspheric Design with 15 Nanometers Wavelength Shift and 0.5° HOE-pair Misalignment.

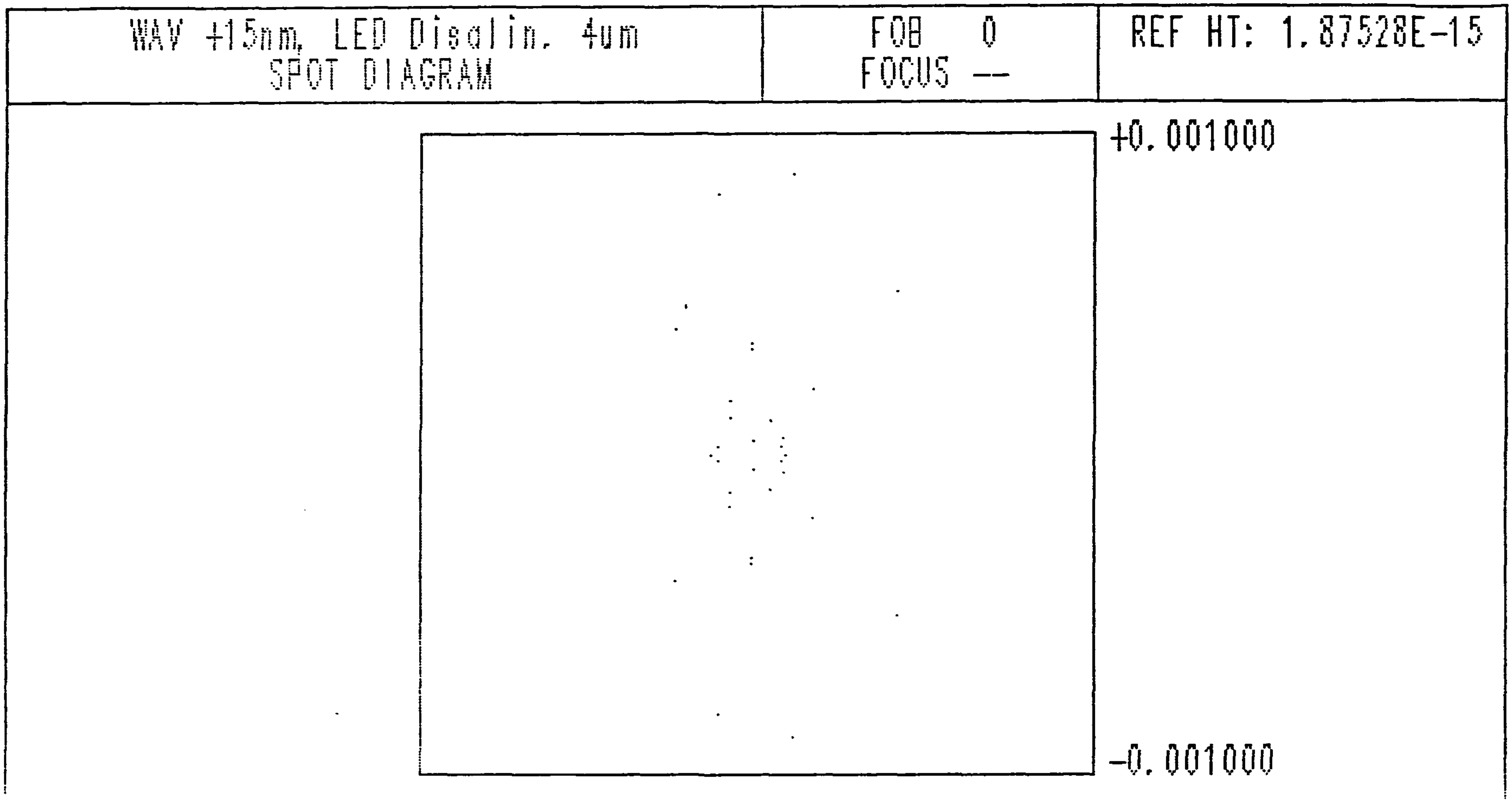


Fig. 11 Spot Diagram: Aspheric Design with 15 Nanometers Wavelength Shift, 0.5° HOE-pair Misalignment, and 4 Micron Laser Axial Misalignment.

In our case, we appear to have attained $\alpha \approx 2.4$ to a point where the intensity is approximately half its maximum value.

Nevertheless, this particular optical head is still a experimental model, and much improvement is possible in the construction of the head, in fabrication techniques, and in measurement of the results. Therefore, work was undertaken to make the optical head more accurate and more practical. This is reported in detail in Section 2.2

**2.2 Optical Head Improvement Effort**

For the past year, we have concentrated our efforts on improving performance of the holographic optical head and in improving our ability to design, predict, and measure that performance.

2.2.1 Improved Test Equipment

In order to determine the spot size more accurately, we developed a highly accurate micropositioner incorporating a piezoelectric drive to improve our knife-edge tester. This has an resolution of 0.1 $\mu$m which can be observed on an electronic position indicator. In this way a more accurate and reliable result can be obtained.

Also, a new test instrument, the SpotScan Model 0390 Optical knife-edge profiler, has been purchased with other funding. When used with a software package available from the manufacturer, measured data can be interpreted automatically and spread functions, spot size and the Strehl ratio, etc. determined. This capability is needed to test the extremely well corrected optical head at the sub-micron level. However, the mechanical configuration of the present test model optical head is not compatible with the detector head of the SpotScan. The very compact head has a small back focal distance (1.3 mm), and there is insufficient clearance to mate it to the SpotScan. We have learned that Photon Inc. has introduced a new measuring head which would make the measurement more accessible in tight spaces. In addition, our next optical head will be designed to be more compatible with the SpotScan.

2.2.2 Investigation of E-Beam HOEs.

Using an e-beam machine to fabricate holograms can avoid very tedious optical alignment work that requires very precise optical and mechanical components and that also needs highly skilled personnel. This method can eliminate many potential error sources, because the e-beam mask can be copied onto a high efficiency substrate. In the long run, making at least the intermediate holograms with an e-beam pattern generator is likely to be both simple and cost effective.

At the present time, however, e-beam generation of high quality holograms is still a subject of intensive research. The availability and performance of e-beam pattern generators have improved significantly during the past several years. Unfortunately, several hurdles remain to be overcome. The most immediate one is compatibility with our data format, which is expected to be resolved with two potential vendors. The others are e-beam resolution and the size of the hologram which can be made at a supportable cost. We have made important progress in this area which is described below.

We conducted a survey to investigate how many institutions have the capability to, and interest in, making complex holograms using an e-beam. To date, we have identified three companies and a university which may be able to satisfy our needs. These are APA Optics Inc., Blaine, Minnesota; Photo Sciences Inc., Irvine, California; Mirage Holography Inc., Dayton, Ohio; and the University of California at San Diego. The survey shows that these institutions have experience in making CGHs at least as difficult as the intermediate HOEs.

The greatest difficulty for e-beam generation of intermediate HOEs lies in translating our output to an acceptable input format for the e-beam pattern generator. UCSD has been very cooperative in this effort, and we have been able to write a computer program to reformat our output suitably for

them. At this time, we can log onto the UCSD computer directly to transfer data and perform calculations. This provides great flexibility and convenience in what will be an iterative process. Unlike some mask houses, there is virtually no wait between sending the data and e-beam generation of the HOE. This will greatly reduce turn around time. This effort is still ongoing as part of a Master's thesis.

Mirage Holography, Inc. uses AutoCad[4] compatible files as the input to their e-beam apparatus, whereas we have been using DesignCAD[5] at the University of Delaware. The output data of our CGH is normally in DesignCad format. Recently we have discovered that the newer versions of DesignCad can produce output in AutoCad format. This effort is also continuing as another Master thesis.

We believe that working with UCSD will provide us with the flexibility and innovative approaches for research related activities. We believe that the Mirage holography Inc. would be a more reliable source and can provide better quality HOE's. We are happy that both have been very cooperative and believe this strategy will assure us the success of this R/D effort.

In principle, by using wet chemical processing for the electron resist and chromium coated quartz reticles, the minimunm feature size of e-beam reticles can be held to less than 0.1 $\mu$m. Thus in the near future, with further R&D effort, it would be possible to manufacture a HOE directly, bypassing the intermediate step. Handling of the vast amount of data can be simplified by using special input and output routines for our CGH program. Routines that transmit data between Super-Oslo and our CGH software (written in Fortran) are largely completed. The CGH program can be run on a Unix based VAX computer or a DOS based PC.

If direct e-beam generation of a working HOE is feasible, it will be the most accurate and simplest technique to use. However, there still remain fundamental question revolving about the use of binary holograms as the working HOE. These are based on experience reported over the last few years. Whether this will be a problem, or even if the high contrast will persist through replication of the reticle, can only be determined by experimentation. In any event, using these improved programs, we are in a much better position to produce e-beam fabricated CGHs for HOH applications.

### 2.2.3 Design Improvements

Improvement in holographic optical head design capabilities is directly related to our calculational abilities. Accordingly, we have recast our existing design software so that it is fully compatible with Super Oslo, a high performance general purpose optical evaluation and design program written for use on AT class personal computers. Super Oslo has been installed on a recently acquired 386 AT giving a speed increase of 4 to 5 times over its performance in its original installation in a 286 AT. Existing subroutines have been improved to utilize the strengths of Super Oslo in ray tracing and evaluation of conventional optics. With this increased capability we are able to perform more extensive analysis on HOH designs and can also extend our designs to more complex cases, for example, the HOH with aspheric lenses.

After extensive analysis of the baseline optical system, we find it can be improved to give wider tolerance of wavelength variation and a smaller diffraction-limited spot. This improvement uses unequal focal lengths for the collimator and objective lenses; the resulting improvement is not surprising, but extensive exploration of design alternatives was prohibited by the computer effort formerly required. A new optical system using two aspherical lens and two holograms has been designed. This new system has a greater tolerance of wavelength variation. See Section 2.1.4 for examples of the new analytical capability.

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[4] AutoCad is a registered trademark of Auto Desk, Inc.

[5] DesignCad is a registered trademark of American Small Business Co.

### 2.2.4 Efficiency Improvements

From the inception of this program, it has been known that high efficiency holograms would eventually be necessary for a working system. It is also known that both multi-level thin phase and volume (Bragg) phase holograms can achieve very high diffraction efficiency, with the latter approaching 100%. Since our final holograms may exceed a spatial frequency of 1,000 lines per mm, a multi-level e-beam hologram will be difficult to made for many years to come. We believe that the development of IR Bragg hologram using a CGH is essential. Our technique for making thin IR HOEs using a CGH can be readily extended to make a Bragg HOE.

It is now quite clear that the HOH's many advantages cannot be realized unless we can improve the diffraction efficiency to above 85 %. Since IR volume holograms can not be directly fabricated by an e-beam, the development of IR volume holograms using a CGH is essential. Once this is achieved, we can then utilize the simplicity, reliability and high performance of HOHs for applications in diverse environments. To this end, the basic mathematical analysis has been done and a mathematical model has been established. To the best of our knowledge, this new approach is unique; no similar work has been reported in the literature. The basic steps are described briefly below and illustrated in Fig. 12.

We use the computer to generate two CGH's. The first is used to generate the distorted reference beam, and second the distorted object beam. For an efficient volume hologram, the Bragg grating condition must be satisfied. For step height $\Lambda$l,

$$2\Lambda\sin\theta_i = \lambda$$

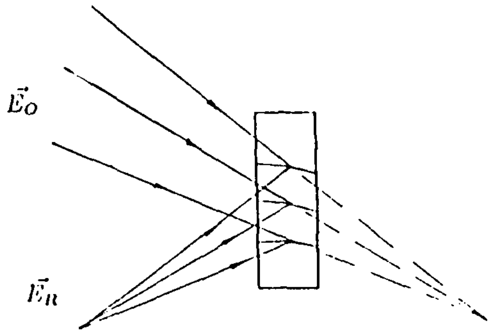
$$\theta_i = \theta_d$$

Like the approach used in calculating CGH parameters in Section 2.1.3, this condition can be used jointly with the eikonal equation,

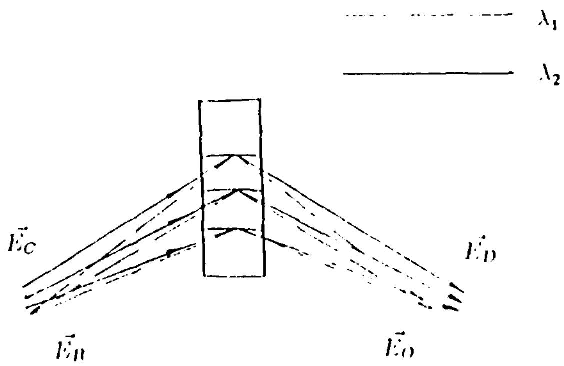
$$\hat{s} = \mathrm{grad}\theta/|\mathrm{grad}\theta|$$

to calculate the interference fringes on the CGH.

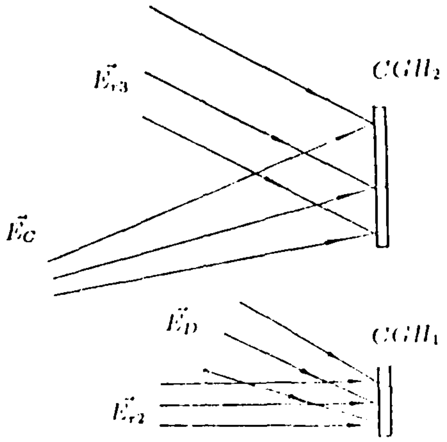
These intermediate CGHs are then produced by an e-beam machine. They are then mounted in an appropriate fixture and illuminated with a laser beam at the visible recording wavelength. The two diffracted beams from the pair of intermediate CGH's will interfere on the hologram plate to form the required IR volume hologram.This simple and elegant approach to generating the Bragg hologram is a natural outgrowth of our use of a single intermediate CGH to produce working HOEs. In the past, the intermediate CGH has been used to modify object beams only. By modifying both the object and reference beam at the same time, we can make IR volume HOEs using a visible wavelength. As mentioned previously, this technique is new and has not been reported by other researchers.



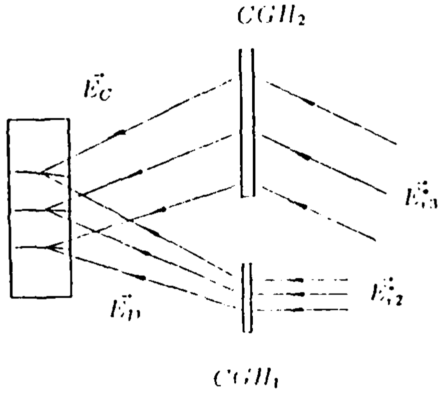

a). Recording a volume hologram with $\lambda_1$




b). Comparison of restoration of a volume hologram using $\lambda_1$ and $\lambda_2$




c). Making CGH for both $E'_r$ and $E'_D$




d). Making a required volume hologram with $\lambda_2$

Fig. 12 Making Volume Holograms with Computer Generated Holograms.

## 3.0 SUMMARY OF CONCLUSIONS, RESULTS, AND RECOMMENDATIONS

We have made significant progress and developed many new and innovative techniques for designing and fabricating a HOH. Our sophisticated computer program, which combines powerful commercial software and in-house programs, allows us to design and evaluate complicated optical systems consisting of conventional optics and arbitrary HOE's. To our knowledge, no other existing software has this combined capability. Our next goals are to realize this capability in a practical HOH and to further expand its functionality and performance.

The following approach seems best suited to achieve these goals:

1. Use an e-beam to make intermediate CGHs for the HOH;

2. Build an engineering model of the HOH based on the optimized new design with two aspherical lenses and two HOEs;

3. Improve the hardware and software of the SpotScan system and link it a computer and plotter so that measurements and analyses can be done automatically and more accurately;

4. Design and fabricate a volume IR hologram to increase HOH efficiency:

5. Investigate new potentials of the HOH which may significantly improve performance. For instance, we can deliberately offset the hologram angles so that the beam is focused at a slightly different position for different wavelengths. Also we can adjust the chromatic compensation so that the focal length simultaneously changes with wavelength in a controlled manner (say by 10 microns). These unique characteristics may allow us to do simultaneous recording (or reading) of multiple tracks on different recording layers. This may also allow us to do tracking or focusing by wavelength tuning instead of by mechanical means, as is now done. These features can become practical when wavelength tunable lasers become available. Such lasers are already available as low power devices. We believe the same techniques can be applied to high power lasers as well. These new capabilities could become a reality in the near future. We must now explore these new potentials to realize major improvements in performance later.

It is important to note that we have laid the foundation to design and fabricate a HOH with the potential to dramatically improve performance. Even more important is that the new understanding of HOE characteristics and novel fabrication techniques could open new applications now considered impractical, e.g., compact high-resolution IR holographic imaging systems and imaging Lidar systems.

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# *MISSION*

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*RADC plans and executes research, development, test and selected acquisition programs in support of Command, Control, Communications and Intelligence ($C^3I$) activities. Technical and engineering support within areas of competence is provided to ESD Program Offices (POs) and other ESD elements to perform effective acquisition of $C^3I$ systems. The areas of technical competence include communications, command and control, battle management information processing, surveillance sensors, intelligence data collection and handling, solid state sciences, electromagnetics, and propagation, and electronic reliability/maintainability and compatibility.*